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CLINICAL REVIEW

The complexities of defining optimal sleep: Empirical and theoretical considerations with a special emphasis on children

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SUMMARY

The main aim of this paper is to consider relevant theoretical and empirical factors defining optimal sleep, and assess the relative importance of each in developing a working definition for, or guidelines about, optimal sleep, particularly in children. We consider whether optimal sleep is an issue of sleep quantity or of sleep quality. Sleep quantity is discussed in terms of duration, timing, variability and dose–response relationships. Sleep quality is explored in relation to continuity, sleepiness, sleep architecture and daytime behaviour. Potential limitations of sleep research in children are discussed, specifically the loss of research precision inherent in sleep deprivation protocols involving children. We discuss which outcomes are the most important to measure. We consider the notion that insufficient sleep may be a totally subjective finding, is impacted by the age of the reporter, driven by socio-cultural patterns and sleep-wake habits, and that, in some individuals, the driver for insufficient sleep can be viewed in terms of a cost–benefit relationship, curtailing sleep in order to perform better while awake. We conclude that defining optimal sleep is complex. The only method of capturing this elusive concept may be by somnotypology, taking into account duration, quality, age, gender, race, culture, the task at hand, and an individual's position in both sleep–alert and morningness–eveningness continuums. At the experimental level, a unified approach by researchers to establish standardized protocols to evaluate optimal sleep across paediatric age groups is required.

Introduction

Sleep duration not only decreases as individuals age, but evidence is accumulating that sleep duration has decreased generally across human society since pre-industrial times [1–3]. The use of artificial lighting, allowing 24 h functioning has had a significant impact on the traditional timing of human activities. There is evidence that both children [4,5] and adults [6,7] are sleeping less than in the past. In fact a widespread claim in both the popular media and academic circles is that we are living in a sleep-deprived society [8,9]. Fragmented or disturbed sleep may reduce sleep duration. Disturbed sleep can be due to untreated sleep or health disorders, or to lifestyle factors. It can be acute (lasting one to two nights) or chronic (lasting multiple days, weeks, months or years). It can occur voluntarily or involuntarily. It is, however, not a new concern.

Sleep loss was described in the Middle Ages as:

"*dangerous to them and greatly to the peril of their bodies….he is much hurt, it wears him out and brings on sickness and untimely old age*" [10]

However it occurs, reduced sleep duration has detrimental effects on waking neurobehavioural functions as well as on a wide range of factors affecting health and wellbeing [11]. Experimental data in adults on the effects of both acute and cumulative partial sleep restriction consistently point out that this has substantial negative effects on daytime sleepiness, motor and cognitive performance, mood, and some metabolic, hormonal and immunological variables [6]. In children, prospective, cross-sectional and sleep restriction studies show short sleep duration is associated with a wide range of negative physical, social, emotional and cognitive outcomes: poor concentration, impaired performance at work or school, increased risk of obesity and metabolic syndrome, depression, suicide ideation and injuries [12–15]. Evidence in experimental studies involving both children and adolescents suggest that cognitive and behavioural outcomes improve if restricted sleep is

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Glossary of terms

CAP	cyclic alternating patterns
EEG	electroencephalography
NREM	non-rapid eye movement
PSG	polysomnography
PVT	psychomotor vigilance task
RCREC	respiratory cycle-related EEG changes
REM	rapid eye movement
SWA	slow wave activity
SWS	slow wave sleep
TSD	total sleep deprivation
TST	total sleep time

restored or extended [16–18]. Together, this evidence suggests that there is an optimal amount of sleep. However, this raises an important question. What is optimal sleep and is it quantity, quality, or is it task-dependent? Or, rather, is there a cost–benefit relationship where the cost of less sleep is weighed against the benefit of increased non-sleep activity? Perhaps, as suggested by Horne [19], sleep is optional to a degree, and sleep need is driven by a subjective notion of sleepiness rather than by evidence of performance deficits? Could "optimal sleep", therefore, be socially constructed and culturally variable? This paper seeks to explore answers, examining the concept of optimal sleep from first principle perspectives in order to develop working definitions for 'optimal sleep'.

Before we advance this discussion, it is important to note that several recent reviews have challenged the popularly-held view that sleep duration in children [9,20] and adults [3] has declined over time. It has been suggested that either the trends in sleep are not as bad as reported [9] or that we are actually getting enough sleep, in that our basal sleep need is lower than generally believed and is less than it used to be. These suggestions necessarily contribute to our discussion of optimal sleep and are important in acknowledging the conflicting evidence regarding assertions of a sleep loss epidemic. Perhaps sleep can be curtailed, perhaps even optionally [21,22], and we have either 'adapted to' or can simply 'cope with' getting less sleep than our forebears did. In fact as early as 1913, researchers Terman and Hocking [23] argued that the key question was, 'What is the optimal amount of sleep for physical and mental efficiency?' Almost 100 y later this question remains largely unanswered.

Is optimal sleep a quantity issue?

Many researchers suggest optimal sleep is a first principle sleep duration issue.

Attempts to ascertain an individual's optimal sleep quantity are based on the idea that 'restricted' or 'deprived' sleep results in a sleep debt, implying an optimal baseline amount of sleep is needed. However, the notion of sleep 'need' is a contested issue attracting much scientific debate [24]. Yet the impact of reduced sleep quantity and the concept of sleep debt lead us to search for the optimal amount of sleep necessary for healthy functioning and performance. Ferrara and colleagues [21] define optimal sleep as "the daily *amount* of sleep that allows a subject to be fully awake (i.e., not sleepy) and able to sustain normal levels of performance during the daytime" while Engle-Friedman and colleagues [25] define optimal sleep as "the *amount* of sleep required to feel refreshed in the morning". With impressive circularity, other studies [17,26] define optimal sleep as the *amount* recommended by authorizing bodies. Eide & Showalter [27] search for this optimal duration of sleep based on how much sleep a student needs to maximize test scores, whereas the seminal paper on which the literature has defined optimal sleep hours for adolescents (9.25 h) is based on longitudinal data involving experimental studies where 19 participants were able to control the amount of sleep they got between 10 pm and 8 am [28].

A shorter sleep duration has certainly been related to reduction of cognitive performance, attention and learning [13–15,20] and to changes to biological markers [29]. Further, evidence pointing to an optimal duration is shown in studies of sleep curtailment where a return to baseline sleep duration produces a corresponding return to baseline performance levels [21,30,31]. These studies certainly suggest an argument for *duration* being a component of optimal sleep. Does this suggest, then, that the more we sleep the better our functioning will be in regard to health and performance? In healthy adults, there is evidence that extending sleep by 2–3 h beyond the norm produces only marginal performance benefits (for review see [21]), or none at all [30]. In fact, whereas extending sleep duration in the short-term appears to improve neurocognitive performance [32], and mood and sleepiness [33], adults who habitually sleep longer than normal have associated risk factors detrimental to cardiovascular health and obesity [34].

If indeed a specific duration is necessary per night, what about cumulative sleep loss? Evidence from several sources [24] suggest that cumulative sleep loss in adults over 14 days of restricted sleep can equate to the equivalent of two days of complete sleep restriction in terms of attention performance as measured by a psychomotor vigilance task (PVT). That is, in short-term sleep curtailment, the effects seem to accumulate linearly. The effects of long-term partial sleep deprivation are less well known, particularly in young people (although neurocognitive and behavioural deficits have been reported over time). One recent study reported cumulative sleep curtailment in adolescents over a school week which resulted in reduced cognitive function and subjective reports of poorer mood and sleepiness [33]. In another, neurocognitive decline was demonstrated after as little as 30 min per night of sleep loss from baseline [18]. Furthermore, studies have shown that three nights sleep restoration in adults [30,31] and one night in adolescents [35] is sufficient to return sleep-deprived individuals to baseline function and performance. This suggests sleep recovery can restore performance but, more importantly, that optimal sleep should be considered over longer than 24 h in order to capture cumulative sleep duration loss.

Clearly sleep duration and its relationship with sleep loss, whether acute or cumulative, will constitute part of an optimal sleep definition. Contributing to the inclusion of sleep duration as a component of optimal sleep relates to early school start times in adolescents. With later bedtimes and inflexible early school start times sleep duration is reduced impacting considerably on daytime behaviour, mood and school performance (discussed below) [16,36].

Is optimal sleep a quality issue?

Sleep quality and sleep consolidation are each essentially measurable through sleep *duration*, but each is more properly an issue of sleep *quality* and needs to be considered [8]. In adults, and under controlled laboratory conditions, Akerstedt et al. [37–39] sought to understand the objective correlates of perceived sleep quality and concluded that sleep quality essentially reflected depth of sleep and sleep continuity. Thus measures of sleep continuity (obtained through diary data [37] or polysomnography [38]) were closely related to the subjective assessment of sleep quality phrased singularly as "how did you sleep?", and rated very well to very poorly, or as an index of sleep quality formed by items with high internal consistency; "calm sleep", "ease of falling asleep", and ability to "sleep throughout" the time allotted. The strongest predictors of the sleep

quality index were slow wave sleep (SWS) and sleep efficiency and variables related to sleep continuity, total sleep time (TST) and the amount of waking [39]. The subjective ease of awakening correlated with poor sleep quality [37] and was predicted by slow wave sleep (negatively) and the circadian maximum of rectal temperature [40].

The laboratory studies described above have been conducted in essentially isolated conditions over several days. Understandably, we are not aware of any child studies conducted with such precision. Sleep quality includes the variability of sleep patterns (for example, the difference between school and non-schools days). For adolescents, this is particularly pertinent because early school start times cannot only influence sleep duration but also poor sleep habits. Later bedtimes and insufficient sleep during school nights lead to delayed wake times during weekends to allow 'catch up' on sleep [16,36]. A study investigating the sleep schedules and daytime functioning in 3000 high school students aged 13–19 y found that 13 y olds were typically averaging close to eight hours of sleep per night whereas older adolescents, 18–19 y olds, were just averaging seven hours per night [41]. The sleep loss observed was due to increasingly later bedtimes in older teens with consistent early wake times to meet school start times with sleep duration increased at weekends in both younger and older teens by an average of 90 min. Later high school start times have been investigated in relation to behaviour and academic performance in a study of over 18,000 US students for the 1996–1997 academic year [42]. School start times were pushed back, by approximately one hour from the original 07:15 h start. Outcomes included improved punctuality and attendance, students feeling more alert and able to work more efficiently, and improvements in academic performance and graduation rates [42,43]. One might question if the students actually used this "extra hour" to get more sleep or squander the extra time on more late-night activities. One study aimed at answering this question found that nearly all of the extra time gained from delayed school start times was invested in morning sleep with bedtimes remaining unchanged [44].

Optimal sleep quality includes the concept of high sleep efficiency ideally with minimal waking after sleep onset. Even brief arousals (micro-arousals) from sleep can reduce sleep efficiency. Interestingly, long awakenings cause much less next-day sleepiness than numerous, albeit brief, arousals [45,46]. Micro-arousals may have little impact on measured sleep duration. They can, however, still render someone quite sleepy. Indeed in Bonnet's study [45], performance decrements after 1 min disruptions to sleep approximated that seen after much more extensive sleep loss. This supported his Sleep Continuity Theory, which states that periods of uninterrupted sleep in excess of 10 min are required in order for sleep to be restorative. Evidence from respiratory cycle-related EEG changes (RCREC) appears to concur with this. These RCREC have been identified and reported by Chervin et al. [47]. In children with sleep-disordered breathing, these brief but numerous micro-arousals are thought to represent a slight arousal of the brain with every laboured breath. They correlate well ($p < 0.01$) with sleepiness in both adults and children, and have been proposed as a possible explanation of neurobehavioral consequences of some sleep disorders. Similarly cyclic alternating patterns (CAP) (an electroencephalography (EEG)-derived measure of sleep instability), investigated in children with and without sleep-disordered breathing [48] show that brief arousals from sleep, not related to respiratory difficulties, can increase sleep fragmentation. This may reduce sleep efficiency to the point where daytime performance is adversely affected.

Circadian rhythm phase can also influence the quality of sleep when misaligned with environmental time cues, as can occur in adolescent sleep related to puberty-related biological and psychosocial factors [49,50]. Misaligned circadian rhythms may result in sleep at the wrong time of the day and other irregular sleep patterns. Indeed, in a recent study, Astill et al. [51] have proposed that circadian misalignment corresponds to excessive sleepiness. Contributing to this circadian misalignment are issues such as cumulative sleep loss over the school week, and weekday–weekend variability in timing and sleep duration (particularly in adolescents) [33,52]. These factors need to be considered when discussing optimal sleep. Should definitions of optimal sleep be considered over a longer period (more than a week) in order to capture this instability of sleep onset and offset described above?

Sleep architecture (the amount and timing of rapid eye movement (REM), non-rapid eye movement (NREM) stages 1 & 2 and SWS) also contributes to sleep quality. An understanding of the relative contributions of these different states in children, as well as their ideal distribution, will be important in defining optimal sleep for optimal daytime performance. Perhaps the microstructure of EEG waveforms is the best indicator. Sleep manipulation studies incorporating deprivation techniques allied to performance measures would be necessary to provide answers to these questions, but such studies are difficult in children because of the strict laboratory baseline conditions required. Furthermore it is impossible to manipulate one stage of sleep without affecting another to some degree. At best we can apply sleep restriction for a limited time, or sleep extension, but few such studies involving children are conducted within the controlled setting of the sleep laboratory.

Is optimal sleep task-dependent?

Clearly, quantity and quality are important in defining optimal sleep but perhaps the question should be how much and what quality of sleep is optimal in order to measure a specific dependent variable? Is "optimal sleep" the amount of sleep required to optimize a particular desirable outcome, such as academic performance or physical fitness and how, if at all, are they different? Historically, task-based analyses form the bases of estimating sleep need and many studies have shown both correlations and cause and effect relationships with sleep variables and performance outcomes suggesting that sleep restriction does lead to detectable deficits in neurobehavioral function and that assessing any changes may depend on the level of complexity of the task. In a recent study, Eide & Showalter [27] explored the relationship between sleep and student performance for children/adolescents aged 10–19 y, estimating the optimal hours of sleep to maximize test score performance of neurocognitive measures. They estimated an age-specific optimal amount of sleep that resulted in the highest value of the predicted test score. This optimal sleep duration changed with age and was based on the type of task. For 12 y olds, participants needed 8 h 20 min to optimally perform letter-word and comprehension tasks, but 8 h 25 min for broad reading tasks. At 16 y of age however, there was general reduction in optimal sleep need for best performance to approximately 7 h. At that age, the most sleep was required for applied problem-solving tasks (7 h 20 min) compared to reading tasks (7 h 1 min–7 h 3 min). According to these data then, differences in 5 min or 15 min can, depending on the task, make a statistically significant difference to optimal performance. The question is, are these indicators also clinically significant?

A further issue is the quality of our waking time. How does the activity undertaken during waking hours (for example a marathon compared to a cognitive task) impact the quality or quantity of sleep? How strongly is this considered within experimental protocols to define optimal sleep? Franken [53] argues: "*from the perspective of a sleep researcher all the action seems to occur during sleep while waking is this other, unappreciated and undifferentiated state that simply fills the time between periods of sleep*." Logically, sleep intensity would depend on the nature of the prior waking experience. Findings from animal studies suggest a direct link

between increases in synaptic plasticity (increases in exploratory behaviour) triggered by waking activities and homeostatic sleep pressure characterized by increases in EEG slow wave activity (SWA) during NREM sleep [54]. Increases in SWA that imply increases in sleep pressure, appear to occur in the absence of changes in sleep duration, suggesting that these parameters can be regulated independently [54,55]. Furthermore, evidence is accumulating that the microstructure of the sleep EEG may also be useful as a marker of intellectual ability in both adults [56,57] and children [58]. In children, Bruni et al. [58] reported higher cognitive efficiency related to an increase of CAP phase A1 in total sleep and in SWS. Phase A is characterized by repeated spontaneous sequences of transient events with the A1 subtype reflecting a predominance of high-voltage slow waves (EEG synchrony) [59].

Is there a linear dose response relationship?

In adults, in the short-term at least, the neurobehavioral effects of sleep curtailment seem to accumulate linearly showing a negative linear relationship with sleep duration, sleep quality and sleep efficiency [24]. Studies of this nature in children are lacking. However, more is not necessarily better. Rather, this relationship may be U-shaped, with both less than [14] and more than [60] an optimal range of sleep being detrimental to performance. Perhaps optimal sleep need may not be a constant dependent on the amount of sleep deprivation.

The notion of optimal sleep may instead reflect a dose–response relationship. As proposed by Matricciani et al, [9] if there is an optimal amount of sleep that is reflected in sleep recommendations, then it would follow that performance outcomes would show an inverted-U pattern where the best performance occurs closest to the sleep recommendations. If the recommended sleep duration is expressed as a range (i.e. 10–12 hours) then optimal performance would occur at a midpoint within that range. This correlates with emerging evidence on some neurocognitive domains [60]. The literature suggests that risk for negative outcomes is reduced within a specific "normal" range of sleep duration, but increases with longer or shorter duration. It might be, therefore, better to understand optimal sleep duration as an optimal *range* of sleep duration. This appears to be the method utilized by Eide & Showalter [27], using the Panel Study of Income Dynamics dataset, to define the optimal sleep needed for various neurocognitive tasks. This study did in fact find an inverted-U relationship between sleep duration and standardized academic test scores. Optimal duration of sleep to produce optimal test performance was about one hour less than the recommended 9.25 h, and decreased with age. The idea that optimal sleep may be a range rather than a set figure also reflects current thinking around published sleep guidelines promoted through organizations such as the American Academy of Sleep Medicine [61].

Alternatively, is it a cost benefit ratio relationship?

There is a well-developed theoretical link between health, human capital and productivity [62]. If an individual has a competitive waking-hours goal, is it more fruitful for him/her to invest in normal sleep patterns, or to stay awake longer to invest in skill acquisition that may in the longer term benefit performance? If a young athlete chooses to reduce sleep duration for competitive advantage, but in the process potentially increases their risk of obesity, sleepiness and reduced neurocognitive outcomes [12], how should we calculate optimal sleep in this equation? A recent nationwide Australian survey [63] reported that reduced sleep duration reflects, to some extent at least, a lifestyle choice by individuals. By sleeping fewer hours, individuals implicitly indicate that the cost of reduced sleep is outweighed by the benefits to them of other activities such as work, school, socializing or exercise.

The International Classification of Sleep Disorders [61] defines the condition of voluntary albeit unintentional sleep deprivation as insufficient sleep syndrome (ISS) where an individual persistently fails to obtain sufficient nocturnal sleep required to support normally alert wakefulness. The prevalence of ISS in the general population is not known but it is diagnosed in about 2% of the patients who present to sleep disorders clinics [61]. Data for children are unknown.

How much ISS is, in reality, voluntary? For instance, how much do cultural beliefs about the benefits of sleeping less and working more impact on this potential cost benefit relationship? Children from relatively high socio-economic groups appear less sensitive to the effect of sleep curtailment on cognitive performance [64]. Perhaps, and related to this, some studies have shown that some cultural or socio-economic groups choose to curtail sleep to increase study time [65,66]. In fact, are we sleeping in the correct fashion at all? The practice of one consolidated sleep overnight may be a manifestation of the modern age. All indications are that humans in pre-industrial times practiced segmented sleep: a first sleep completed before midnight, followed by a second beginning some 3–4 h later and lasting until morning [67]. Since the Middle ages, giving up sleep to increase earning or output capacity has resulted in the "voluntary" curtailment of sleep for many people [10].

Is optimal sleep a social construct? Or does this reflect individual subjective assessment of sleepiness and fatigue?

If optimal sleep is in fact partly a social construct, and therefore to some extent optional, the links described in the literature, between sleep curtailment and reduced performance and/or health outcomes may not be as important. Shifts in sleep duration across the decades [4,5] might be biologically driven by a brain needing less sleep. Alternatively, these changes might be the result of entirely external forces, either choice-driven (such as socializing and human capital investment), or from necessity (such as having to get up for school) [68]. Supporting this, a meta-analytic study by Ohayon et al. [69] suggests that the plateau effect of similar sleep duration between ages five to the adolescent years can be explained by the external drive for reduced sleep at the adolescent end. In addition, large individual differences in how a variable is affected by restricted sleep will affect the possibility of detecting significant results. This is so, even when using correct statistical procedures which partly counteract this.

Other possibilities need to be considered. For example, Horne [19,22] suggests that feelings of sleepiness do not necessarily indicate a need for more sleep, but merely a desire to sleep. Is sleepiness therefore a subjective notion and a social construct, or a 'true' physiological indication of needing more sleep? Indeed, Malone [70] suggests that although sleep hygiene practices are choice- and potentially culturally-driven, they are not solely a social construct. Rather, they combine both biological sleep needs and societal expectations. If so, this would no doubt impact on the cost/benefit relationship of sleep need in a bi-directional fashion.

However there is recent evidence in children that subjective sleepiness is a major factor in performance challenging that it is more than just a perceived need or subjective notion, as suggested by Horne [19,22]. In a recent study, van der Heijden et al. [71] report that parent-reported sleep significantly mediates the effects of eveningness on behavioural problems, working memory and sustained attention. Subjective sleepiness (not feeling rested upon awakening), was the key mediator in this relationship, not sleep duration. In other words, sleep quantity may be less important than feelings of sleepiness. Subjective sleepiness seems to occur when wake times happen before the circadian drive for

arousal and prior to complete dissipation of sleep pressure. In our culture, this is common during weekdays, particularly in adolescents [72]. This corresponds to previous findings that subjective sleepiness is strongly associated with cognitive performance in children [73,74]. Indeed Andrade et al. [72] report that more than 90% of adolescents report sleepiness regularly during the school day. In van der Heijden et al.'s study [71] the subjective sleep quality index *feeling more rested upon waking up* showed favourable associations, particularly during weekdays, with many cognitive and behavioural measures: faster simple reaction time and sustained attention reaction time, more sustained attention stability, faster working memory reaction time, and fewer behavioural problems. Concurring with previous studies in children and adolescents [72–74], this suggests that the subjective quality of sleep and sleepiness may be a helpful indicator of insufficient sleep and secondary daytime sequelae. Thus, in the absence of clear guidelines about optimal sleep needs, subjective sleepiness – already shown to be a potential indicator of sleep loss above – may be very important in evaluating *individual* sleep need.

Sleepiness as a marker for sleep need in children is however challenged by the concept that lack of sleep may manifest differently in children compared to adults, as concluded by Dahl [13]; adults display tiredness, while children may display more externalizing symptoms. The general pattern cited includes difficulties with focussed attention, irritability, emotional lability, and low-threshold for frustration and distress [13]. This may only apply to younger age groups; adolescents with shorter sleep duration report more subjective sleepiness than children [41] and objective measures of sleepiness (such as the Multiple Sleep Latency Test) have also revealed that before puberty, children often show less daytime sleepiness than adolescents or adults [28].

Outside of the sleep laboratory, the caveat to using sleepiness as an indicator of sleep need in children is that the assessment of sleepiness is complicated by the difficulty of self-reporting. In younger children, parental report is the hallmark of data collection, as reporting sleep behaviours requires higher order cognitive processing which are not acquired until after 8 y of age [75]. However, even in older children, where parental accuracy may shift as supervision needs change and sleepiness may not be observed during the school day, reporting of sleepiness and therefore assessment of its relation to optimal sleep is problematic [76].

How significant is the socio-cultural component of sleep? Studies have demonstrated that socio-cultural and racial differences in sleep patterns exist and should be addressed if one considers optimal sleep tailored according to known individual differences [77–82]. Mindell et al. [79,82] for example report shorter nighttime sleep of infants and toddlers [79], and 3–6 y olds [82] from predominantly Asian versus predominantly Caucasian countries. However because daytime napping continues for longer in Asian children, they found no difference across cultures in TST over 24 h in 3–6 y-olds [82]. A meta-analysis of 41 surveys of worldwide adolescent sleep patterns shows that adolescents from Asian countries have later bedtimes than their European or North American counterparts, obtain less sleep and tend to report higher rates of daytime sleepiness than adolescents from other regions [80]. These cultural influences are virtually ameliorated on the weekends with adolescents across the world demonstrating delayed bedtimes and wake-up times of greater than 2 h.

Is optimal sleep need the same for every child and young person?

So if individual sleepiness is a good predictor, then what of individual differences? For example, if a child's sleep duration falls into the 90th percentile compared to a reference population such as those described in numerous meta-analyses of sleep durations across childhood [4,5,81] it is still quite possible that the amount of sleep acquired is inadequate. However for another child, the same amount of sleep may be sufficient for healthy functioning and performance. Does this suggest that we can simply 'cope' with less sleep? Does this account for the changes in sleep duration over the last 100 y? [5].

Perhaps by focussing on individuals with sleep phenotypes outside the range of normal (e.g., naturally short or long sleepers) we could establish cut-offs and facilitate a working definition for optimal sleep. Researchers are therefore particularly interested in adults who are naturally short or naturally long sleepers [83]. It would be useful to understand the factors that make short sleepers resilient to sleep deprivation. Despite a strong genetic link [84,85], we know very little, if anything, about habitual short sleepers in childhood. Defining naturally short sleepers correctly is critical for any study design, which must exclude those who perceive they have a short sleep propensity, but whose reduced sleep is in reality driven by scheduling [86]. In children, there is also reduced capacity to self-report. Researchers must therefore rely on parental accuracy in reporting their child's sleep and factors driving this. Reporting whether a child has sufficient sleep is based largely on parental report. Yet parental report is known to be less sensitive and, in some cases, less reliable than self-report, particularly as children get older [76]. Furthermore the setting of any study is important. For example one study reports shorter sleep duration in children associated with teacher-reported, but not parent-reported, behavioural problems [87].

Many studies have reported that difficult temperamental predisposition in infants [88], pre-schoolers [89] and school aged children [90,91] can negatively impact on sleep. Do children with better coping skills or more positive temperaments cope better with less sleep or perhaps even *need* less sleep? Is it that not only that there are differences in sleep need, but also differences in how individuals react to less sleep? This could be described as a temperamental predisposition to sleep loss. Several studies investigating the recovery of neurobehavioural functioning following experimental sleep restriction or total sleep deprivation (TSD) demonstrate that when recovery opportunity is greater than eight hours, impairments in neurobehavioral function recover to baseline levels after one to two days of extended sleep [92–95]. In contrast, other studies have found that complete recovery from sleep debt may take more than three days of extended sleep [30,96]. Do individual differences play a part in these conflicting results? These individual differences have been rarely considered. Inter-individual differences in sleep duration in children and adolescents are influenced by variation in sleep need, sleep problems, and sleep restriction through exogenous factors (e.g., limit-setting problems, presence of a television or computer in the bedroom) or endogenous factors (intrinsic sleep disorders, genetic predisposition) [97,98]. We do know for example that individual differences in circadian preference exist. Individuals can be classified as morning, evening or neither, although criteria to classify children are lacking. Half the variance in circadian preferences is genetically determined [99] and the trait remains considerably stable during human development despite the marked shifts towards eveningness in adolescents [49]. Behavioural, emotional (including suicidality and drug abuse) and academic problems are worse in adolescents with evening types compared to morning or intermediate types [100–103].

Finally gender differences in childhood may be important as boys sleep on average somewhat less than girls [104,105]. Young males show reduced sleep duration and more sleep variability (greater differences between week and weekend sleep) compared to females [106,107]. In addition, these differences increase with

age so discussions of optimal sleep would necessarily need to be both age and gender specific.

Research challenges for establishing optimal sleep

Understanding optimal sleep in children is a complex issue with some researchers comparing this to the 'search for the philosopher's stone" [21] particularly as undertaking research in children within experimental paradigms is challenging. Realistically, research precision requires strict sleep laboratory conditions and sleep deprivation protocols-ethically hard to justify with isolated conditions. However, to understand optimal sleep in children from the perspective of inputs at a physiological level and outputs at a neuropsychological or behavioural level, polysomnography (PSG) studies are necessary. Although many devices on the market now enable the microstructure of sleep to be studied in the home, strict experimental manipulation is difficult. Thus the literature appears full of protocols representing researchers' best attempts' under the circumstances. Perhaps engaging children in this type of research is the key. Van Someren's research group adopted a child research-friendly approach to studying children in the sleep laboratory [108]. A whole classroom of children simultaneously underwent a full overnight PSG while sleeping in a dedicated sleep lab built on location in a science museum. They used an all-inclusive approach, only applying exclusion criteria prior to analysis. Buddy systems, consulting children in research design [109], making them owners of the research, are all novel approaches to adopt in the quest to understand the biological processes underpinning sleep needs in children. An approach to predict the resilience and vulnerability to sleep loss of adult individuals has potential application for children. Rajarman et al. [110] have used a mathematical model to predict future performance of adult individuals with uncertain initial state and unknown trait characteristics, based on previous vigilance task performance following sleep deprivation. To be able to predict decline from a short period of sleep deprivation, without subjecting children to periods of sleep deprivation longer than necessary, is an attractive proposition.

Summary and conclusion

Above we attempt to elucidate the complexities in defining optimal sleep so we can begin to understand how sleep guidelines may be developed more empirically therefore assisting in health policy and education. It is indeed a difficult task but one that needs to be undertaken nonetheless. Ferrara & De Gennaro [21] were perhaps correct in saying that "the amount of sleep we need to be at our best is as individual as the amount of food we eat". Fig. 1 brings our discussion together to illustrate the interacting factors driving optimal sleep. Optimal sleep, (sleep duration, sleep quality, cultural, individual and societal factors) may be fluid and task dependent, operating under the banner of a cost/benefit ratio in today's society. In addition, as large individual differences exist in the need for sleep, searching for a simple definition is made even more difficult. A somnotypology, taking into account duration, quality, age, gender, culture, race, the position in both the sleep–alert and the morningness–eveningness continuum, and the task at hand, may be the only method of capturing this elusive optimal sleep. Normative curves across populations is a critical step towards better understanding sleep duration across cultures and populations. The literature cites many different approaches for assessing optimal sleep in children however, it is clear a tremendous amount of additional work is needed to identify "optimal" sleep for an individual, patterning of sleep duration across the lifespan and its correlates, and the biological and non-biological influences on these observed differences in sleep duration within individual children. But "what is optimal sleep?" may be the wrong question. Whilst this promotes healthy discussion of the validity of current sleep recommendations in children [9,20,111,112], the ongoing lack of consensus on the issue suggests perhaps rethinking the direction that is taken. Maybe a more critical, practical and useful clinical question is: "What factors best determine how much sleep each individual child needs to function optimally? A unified approach by researchers to establish standardized protocols to evaluate optimal sleep across paediatric age groups is required. This necessitates developing standardized sleep restriction/extension protocols, and defining the best age-appropriate measurable tasks for performance.

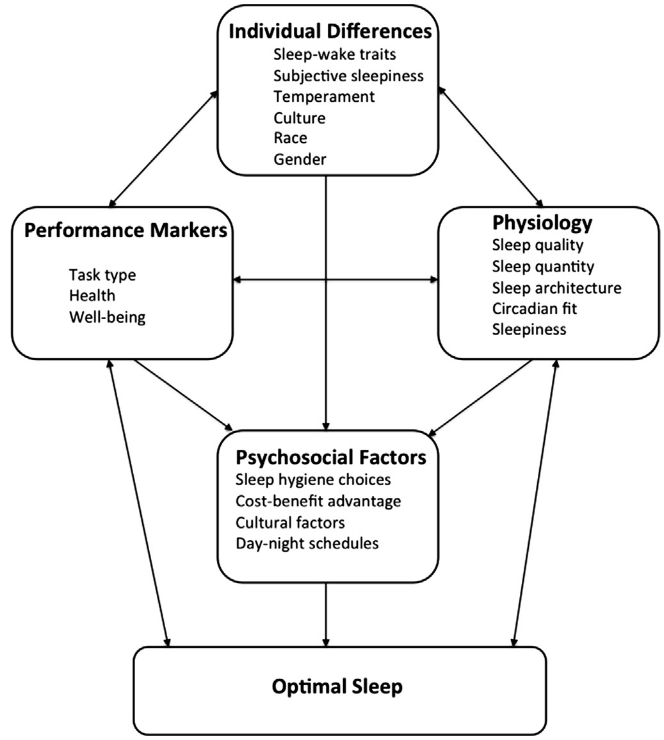

Fig. 1. Schematic representation of factors impacting on the definition of optimal sleep.

Practice points

- Evidence that less than optimal sleep in children has detrimental effects on waking neurobehavioural functions and a wide range of factors affecting health and wellbeing is well established and leads us to question what is optimal sleep?
- Defining optimal sleep need in children is complex.
- Definitions need to encompass physiological, psychosocial, and neuropsychological factors, many of which reflect significant individual differences.
- Undertaking research in children within experimental paradigms and maintaining research precision is challenging.
- Alternatively, a optimal sleep could be simply defined through individual subjective assessment of sleepiness since recent literature shows this links strongly with performance.

Research agenda

- More research in children is required to evaluate the importance of subjective sleepiness on daytime performance.
- Given the myriad of existing protocols, assessing optimal sleep in children experimentally requires a unified approach by researchers to establish standardized protocols to evaluate optimal sleep across paediatric age groups.
- Developing suitable sleep restriction/extension protocols and defining the best measurable tasks for performance is required for this.
- Empirical evidence from many similar studies could then be incorporated into simple algorithms to create somnotypes for individuals.

Conflicts of interest

The authors do not have any conflicts of interest to disclose.

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